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THE STUDY OF MULTIPACTOR BREAKDOWN
IN SPACE ELECTRONIC SYSTEMS

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Culver City, California

A. OBJECT OF CONTRACT

Multipactor discharges have been observed in a variety of space-borne radio frequency equipment, and are a potential source of system degradation or equipment failure. The object of this study program is to define conditions under which multipactor discharges can occur in representative space hardware, to evaluate the effects of a discharge when it does occur, and to investigate possible techniques for prevention of multipactor which are compatible with other equipment requirements. The work is divided into the following three tasks:

- | | |
|-----------|-------------------------------------|
| Task I. | Investigate the Multipactor Effects |
| Task II. | Deleterious Effects of Multipactor |
| Task III. | Methods of Eliminating Multipactor |

B. WORK PERFORMED DURING THE REPORT PERIOD

SUMMARY

This report describes work done during January 1965. During this month successful high vacuum (pressure less than 10^{-9} mmHg) discharges have finally been obtained, using beryllium copper electrodes. Measurements have been made of both harmonic and noise currents in the electrode structure, and intermodulation distortion coefficients have been determined. Tests run on titanium coated electrodes have shown an enhancement of multipactor, rather than the expected suppression. An experiment has been started in which the effect of DC bias on both single and double surface discharges can be evaluated.

DETAIL REPORT

As has been mentioned in previous reports, the active lifetime of a multipactor discharge between common metals such as aluminum, silver, or gold plated brass is at most a few hours at pressures of 10^{-5} to 10^{-6} mm. During this time the discharge power decreases steadily, and a point is usually reached where a discharge cannot be obtained. The effect, which has been noted by many experimenters, is almost certainly due to reduction of the secondary emission ratio of the

electrode material as a result of contamination by residual gas and by organic material from the vacuum system.

In an actual unpressurized spacecraft environment the local pressures may have any value from a few mm down to perhaps 10^{-12} mm, depending on the external pressure, local outgassing, and the extent of venting to the exterior of the spacecraft. While any multipactor activity would probably cease after a few hours of operation at the higher pressures, sustained discharges are to be expected when the pressure is below about 10^{-9} mm. As described in the second report, * an experiment has been built to permit operation of a discharge at pressures in the range of 10^{-9} to 10^{-10} mm in order to allow evaluation of various electrode materials and measurement of the electrical properties of a stable discharge. Despite considerable difficulty, ** this experiment is now operating satisfactorily and tests are being conducted.

For the first high vacuum tests the electrodes used were copper which had been treated with an organic magnesium salt. (This material was chosen because it has been found to be a stable secondary emitter when used in a controlled atmosphere at considerably higher pressure.) After extended bakeout the pressure was reduced to

*See Figure 2. c. , page 6.

**In order to reach these low pressures it is necessary to bake the vacuum chamber and the experimental apparatus at a temperature of 250°C for 24 hours or more. In light of this rather extreme treatment, there is considerable doubt that pressures as low as 10^{-9} mm will ever be reached in the interior regions of spacecraft, even if they are fairly freely vented. The vacuum chamber used in these tests is about 6 inches in diameter and 12 inches long, and is pumped through a 6 inch port in the long side by a 125 liter per second pump, which is equivalent to a 1.5 inch diameter orifice opening into a perfect vacuum. Although both the equipment and the chamber are carefully cleaned before evacuation begins, the ultimate pressure of this system at room temperature is about 2×10^{-8} mm. In a typical spacecraft installation the equipment may be installed in a bay with a comparable volume, but with a much smaller opening to the external pressure. Furthermore, the surface area inside the bay may be quite large (particularly if multi-layer aluminized mylar heat shields are used), and there may be considerable contamination by relatively high vapor pressure materials.

8×10^{-10} mm and RF voltage was applied. As the voltage was varied through the optimum value for multipactor a momentary fluorescence of the detector phosphor was occasionally noted, together with a slight current to the collector plate. However, no sustained discharge could be obtained and no experimental data were obtained. The electrodes were exposed to air and then the system was pumped down to 10^{-6} mm and RF power applied. Under these conditions a strong discharge was obtained. No further experiments were run with this electrode material since it had become evident that beryllium copper would probably make more useful electrodes.

A pair of bright dipped beryllium copper electrodes were installed, and the chamber was again evacuated. When the pressure reached 4×10^{-6} mm RF voltage was applied and a strong discharge rated with a collector current of 80 microamperes. Power was removed and the assembly was then baked out and pumped until a room temperature pressure of 6×10^{-9} mm was reached. RF power was again applied and a strong discharge was obtained, as indicated by fluorescence of the detector phosphor and a flow of collector current. Initial collector current was 80 microamperes, the same value noted at 4×10^{-6} mm. During two hours of operation at the same power level the current increased and then stabilized at 180 microamperes (see Figure 1). At this time the power input was reduced until the collector current was 160 microamperes, and the test was then continued for fifteen hours at this same power level. At the end of the test, the chamber pressure had dropped to 1.8×10^{-10} mm and the collector current was 158 microamperes, indicating that, within the stability of the measuring equipment, no change in multipactor level had occurred.

In order to verify the previous observations of electrode-deterioration at higher pressure, a leak was introduced into the vacuum system, the pressure was increased to 10^{-6} mm, and RF power was applied. The initial collector current was 220 microamperes, and it dropped to 168 microamperes at the end of 3-1/2 hours of operation, as shown in Figure 2. While the current decreased

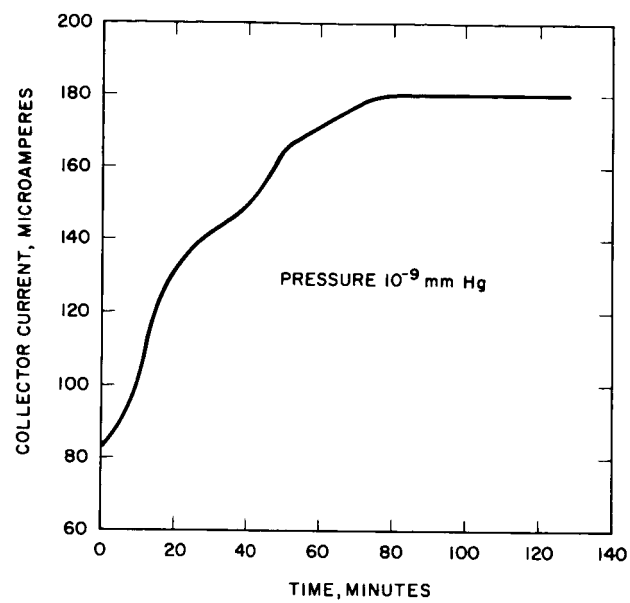


FIGURE 1. BERYLLIUM COPPER ELECTRODES

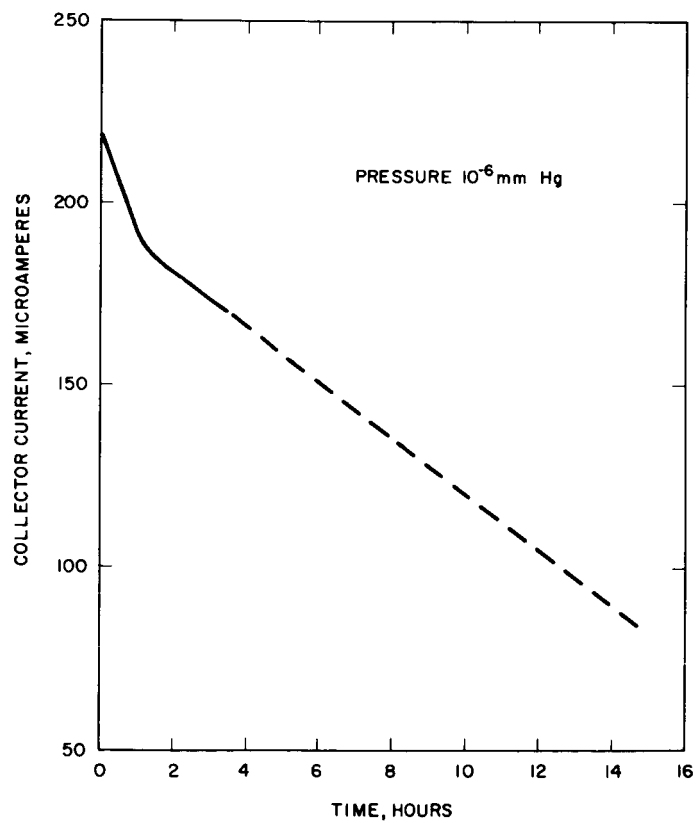


FIGURE 2. BERYLLIUM COPPER ELECTRODES

steadily during the run, the rate of decay was not as great as that which is usually observed, probably because the residual gas was air without any organic contamination.

The equipment was left operating for an additional 16 hours. At the end of this time the chamber pressure had dropped to 4×10^{-9} mm, the collector current was 135 microamperes, and the detector phosphor (which had ceased to glow at the end of the 3-1/2 hour run) glowed brightly. This tends to confirm previous observations that exposure to high vacuum will at least arrest the deterioration of the electrodes, and probably restore their activity. In future tests more common materials such as aluminum, gold plated brass, tin, and copper will be tested under similar conditions in order to compare their multipactor properties at high and low pressure.

One conclusion which can be reached from these preliminary results is that tests of spacecraft equipment should be conducted over the full range of pressures at which it will actually be operated, at least insofar as multipactor behavior is to be evaluated.

Many system vacuum tests are run in the 10^{-6} mm range, where a discharge may last for only a few minutes and perhaps escape observation. If, in subsequent operation, the pressure were to drop to the 10^{-9} mm range or below multipactor activity could return and remain permanently, although the equipment had apparently passed a "vacuum" test.

One of the important parts of Task III of the contract is item (e) II - "Analyze observations and measure performance to determine seriousness of problem, i. e., if cure is absolutely necessary." Most of the measurements of discharge impedance, harmonic generation and intermodulation, and noise generation have been directed toward answering this specific question, and some general comments can now be made. First, no "catastrophic" multipactor events have been observed in any tests. The maximum power loss observed has been only 135 milliwatts per square inch of electrode area, with more typical values being 60 mw/in^2 or less. Furthermore, these measurements were taken under conditions which are not likely to be

encountered in actual equipment -- plane parallel electrodes and spacing optimized for the frequency and voltage (180 volts, 5/8 inch plate spacing, 100 mc frequency). At higher frequencies and voltages the power will be higher, but it seems unlikely that any of the so-called "catastrophic" failures (400 mc OAO filter at Hughes, 960 mc coaxial structure at JPL and RCA) in which severe burning or pitting were observed could have been the result of multipactor alone. A more reasonable explanation is that they were the result of an arc initiated by a gas discharge which resulted from high gas pressure due to local outgassing caused by multipactor induced heating. It is significant that such effects have been observed only in tightly confined volumes.

Under many conditions in which a multipactor discharge can take place the power loss will be low enough to be ignored and only the accompanying electrical phenomena will be of importance. A more detailed knowledge of the magnitude of these effects is necessary before predictions can be made of the effect of multipactor on a given system. While multipactor in a diplexer or antenna feed system may cause desensitization of an associated receiver due to noise or spurious signal generation, in other cases there may be no problems at all and the multipactor can be tolerated. In any event, the importance of testing a complete system under actual operating conditions is obvious.

Because of problems in coating the interior of the coaxial resonators with titanium, ** a preliminary experiment was run with pair of copper electrodes coated with a titanium film, 383 angstrom thick. Two experiments were run at the same time, each using the "standard" 100 mc structure. *

One structure had the titanium coated electrodes. The equipment was installed in the Veeco vacuum chamber and the pressure was reduced to about 10^{-6} mm, at which time RF power was applied to both circuits and collector current was measured as a function of time, as

*See Figure 2, page 6, of the Second Status Report.

**Titanium metal has a secondary emission coefficient less than unity, and should in principle be an effective multipactor suppressing agent.

shown in Figure 3. Over the operating time of the test the intensity of the discharge with the titanium coated electrodes was always greater than with the copper plates, and the difference increased with time.

The most probable explanation for these results is that the titanium film had oxidized rapidly on exposure to the atmosphere and that the resultant titanium oxide layer was a relatively good secondary emitter. In the use of titanium films for suppressing multipactor in high power microwave tubes this oxide layer is usually reduced to metallic titanium by heating the entire device to 350°C in a vacuum,^{*} but it is thought that the same reducing effect occurs under bombardment by multipactor electrons. While this may be true with high power discharges, in this experiment there was no evidence of the expected multipactor suppression which should have resulted, and since high temperature vacuum bakeout of assembled electronic equipment is impractical, no further investigation of titanium films will be conducted.

The third status report described the results of a series of tests in which part of the multipactor electron cloud was collected and analyzed for harmonic and noise content. While measurement of the electron current simplified the tests by providing isolation from the fundamental RF field, in an actual operating circuit the net electrode current (difference between primary and secondary electron current) is of more interest. During this period the tests were extended to measurement and analysis of the current flowing in the low voltage (near ground) discharge electrode. A 3.3-ohm resistor was placed in series with this electrode. The current waveform signal from this circuit as well as the voltage from a capacitively coupled pickup plate located near the high potential discharge electrode were each connected through attenuators to two channels of an HP-185A Sampling Oscilloscope (see Figure 4. a.). Measurements were first taken without the 100 mc rejection filter but it was found that the fundamental current due to capacitance between the electrodes obscured multipactor effects.

^{*}Talcott, Ruth C. , "The Effects of Titanium Films on Secondary Electron Emission Phenomena in Resonant Cavities and at Dielectric Surfaces," Trans. IRE PGED, September 1962.

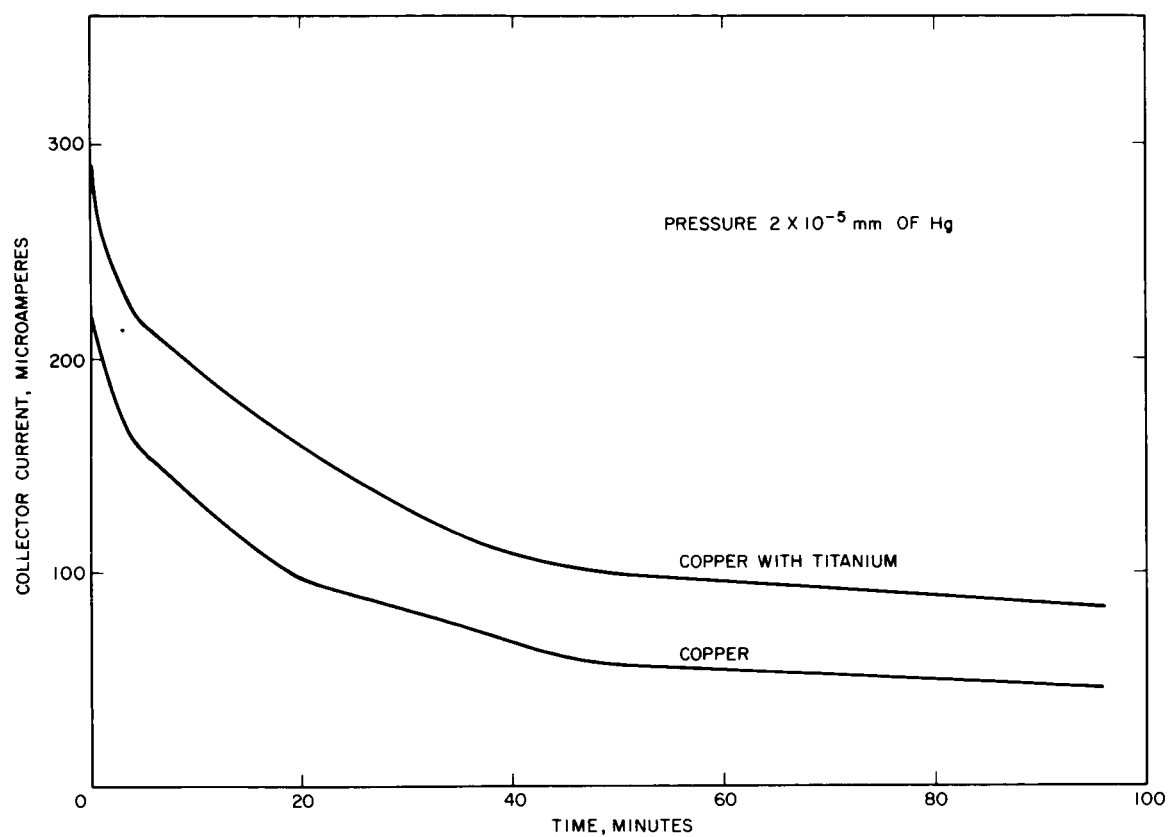


FIGURE 3. COPPER AND TITANIUM COATED COPPER ELECTRODES

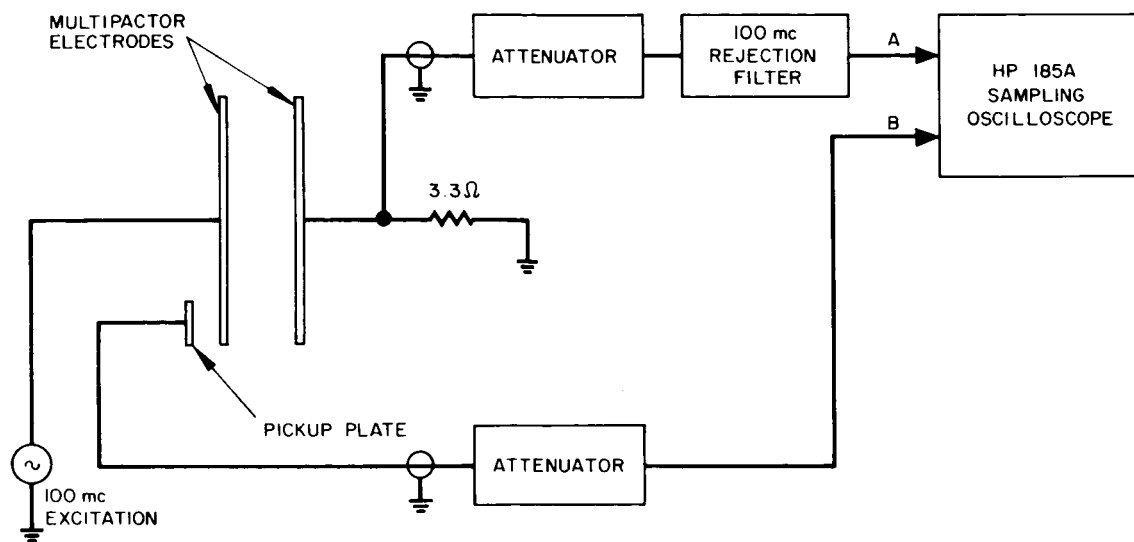


FIGURE 4a. ELECTRODE CURRENT MEASUREMENT USING FILTER

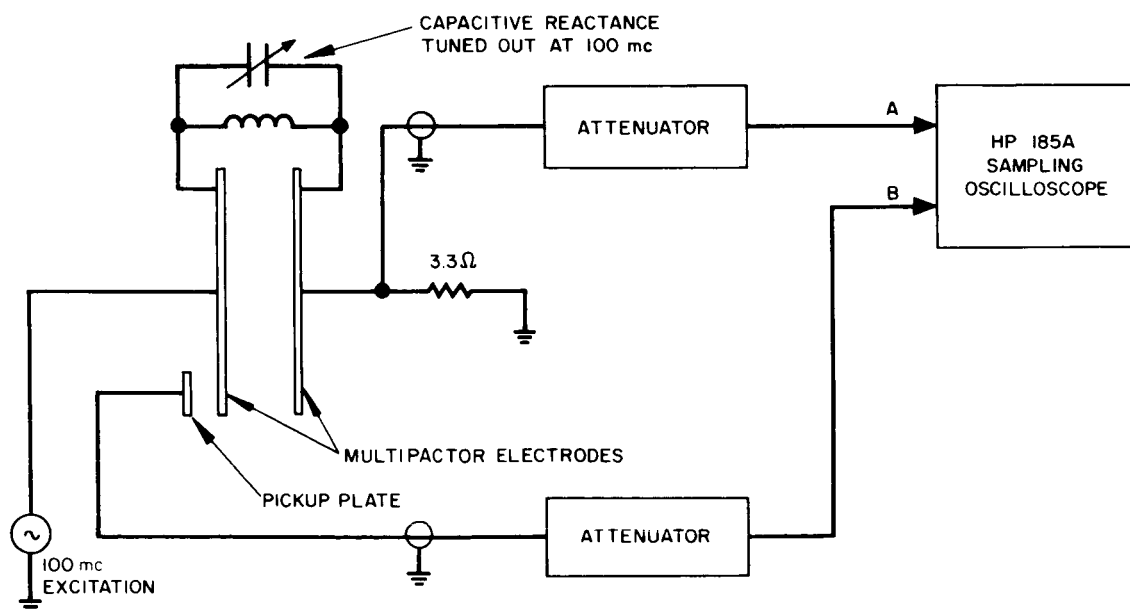


FIGURE 4b. ELECTRODE CURRENT MEASUREMENT WITH REACTANCE TUNING

The rejection filter was inserted to eliminate the 100-mc components and current waveforms were obtained which showed prominent third harmonic components when multipactor was present.* To obtain information on the fundamental component due to multipactoring, a parallel resonant tuned circuit was added to cancel the capacitive reactance at 100 mc, as shown in Figure 4. b. With the tuning capacitance adjusted for minimum fundamental amplitude the multipactor current waveform was about 10 times greater than the remaining stray signal amplitude, and contained 2nd and 3rd harmonic components. By means of a Fourier analysis the amplitudes of the components were determined. The results of these tests are summarized in Table I. For each measurement the electrodes were 5-inch diameter beryllium copper discs spaced 3/4-inch.

The results of the harmonic measurements described in the third status report** were used to evaluate the second and third order nonlinearities of the discharge current/electrode voltage relation. If we assume the discharge (electron) current is related to the electrode voltage by a power series such as

$$I_d = K \left[a_1 V_e + a_2 V_e^2 + a_3 V_e^3 + \dots \right]$$

and the electrode voltage is a sine wave of amplitude A volts and frequency ω_1 , the harmonic content of I_d is, in terms of the power series coefficients,

$$I_d = KA \left[\left(a_1 + \frac{3}{4} a_3 A^2 \right) \cos \omega_1 t + \frac{1}{2} A_2 \cos 2\omega_1 t + \frac{1}{4} a_3 A^2 \cos 3\omega_1 t + \dots \right]$$

with any DC term neglected. From a Fourier analysis of the discharge current waveform the harmonic amplitudes can be determined, and the coefficients a_1 , a_2 , a_3 , can be computed. If the main signal components of interest are the harmonics themselves the evaluation is complete at that point.

*The equipment is operated at atmospheric pressure to obtain comparison measurements without multipactor.

**See Figure 1 and Table I

TABLE I. Summary of Electrode Current Harmonic Measurements

Electrode (volts)	Multipactor (watts)	Electrode Current		Notes
		I _{pk} amp	f MC	
100	0.50	1.1	100	Figure 4. a. (without rejection filter)
110	0.90	1.2	100	
100	0.76	0.039	300	Figure 4. a.
120	0.49	0.27	100	Figure 4. b. (capacitance tuned out and Fourier analysis used)
120	0.49	0.030	200	
120	0.49	0.027	300	

Since most spacecraft transmitter-receiver systems would be designed to avoid receiving frequencies on or near harmonics of the transmitter frequencies, the direct harmonic terms probably would not cause significant interference. However, both cross modulation (transfer of signal modulation from a large to a small signal) and intermodulation (generation of spurious signals) will also occur in a non-linear element, and either could cause trouble. Let us consider the case of a diplexer in which both transmitter and receiver might be coupled to a circuit in which a multipactor discharge would be initiated by the transmitter signal. Let the transmitter voltage at the discharge be A volts at frequency f_1 , and the small signal be B volts at frequency f_2 . The resultant multipactor current will contain components of frequencies of f_1 and f_2 and all their harmonics, plus the sum and difference of all these frequencies. Interference to the receiver will probably be caused by difference frequencies near to the original signal frequencies. If f_1 and f_2 are nearly the same the most significant intermodulation component will be at a frequency of $2f_1 - f_2$. For example, if the spacecraft transmitter signal causing multipactor (f_1) is at 136 mc a small signal at 149.1 mc would produce a signal at 122.9 mc.

Table II shows the relative magnitudes of the three largest components of discharge current, computed from the measured

TABLE II. Important Intermodulation Components

Frequency	Amplitude Equation	Relative Amplitude (Coefficients Substituted)
f_1	$A (1 + \frac{3}{4} a_3 A^2)$	1.49 A
f_2	$B (1 + \frac{3}{2} a_3 A^2)$	1.98 B
$2 f_1 - f_2$	$B (\frac{3}{4} a_3 A^2)$	0.49 B
$2 f_2 - f_1$	$A (\frac{3}{4} a_3 \frac{B^2}{A^2})$	$0.49 (\frac{B}{A})^2$

harmonic coefficients. The magnitudes of the signal at frequencies f_1 and f_2 are given with respect to the value they would have if the discharge current had no non-linearities. The magnitude of the small signal current at f_2 is almost double the value it would have if the signal at f_1 were not present, indicating that there would be a strong transfer of amplitude modulation from signal A to signal B, or that signal A tends to suppress signal B. Note that in this example the currents represent conversion of signal energy into multipactor electron energy, and an increase in the electron current increases the circuit loss. In order to calculate the actual percentage change in power loss it would be necessary to know the exact coupling of signal power to the discharge electrodes. In addition to the signals at f_1 and f_2 there is a signal at $2f_1 - f_2$ which is comparable in magnitude to signal B and proportional to it.

Measurements of multipactor noise were continued during this period, using the techniques described previously. The experiments were designed to compare various pickup methods, and in particular to differentiate between noise picked up by capacitive coupling and noise due to direct interception of multipactor electrons. In general the noise levels were comparable to those observed previously (of the order of 10^{-18} watts per cps). The data are being analyzed and the results will be contained in a subsequent report.

An experiment has been set up to evaluate the effect of DC bias on multipactor, and to obtain single surface multipactor. One electrode is a 5 inch diameter beryllium copper plate and the other is a coarse (1/4" mesh) screen which can be given a variable DC bias. In preliminary tests both single and double surface multipactor have been observed, and the ability of the DC bias to suppress the discharge has been measured. A detailed description of the experiments will be given in the next status report.

C. PERFORMANCE AND WORK SCHEDULE

A total of 600 equivalent manhours was spent on the project during January, divided among the tasks as follows:

Task I	44 hours
Task II	200 hours
Task III	356 hours

The program is on schedule and should be completed by 15 March 1965.

D. CONTRACT FUNDING

Present funds are adequate to complete the program on schedule. The planned equivalent manpower schedule for the remainder of the contract is as shown below:

	Manhours	
	<u>February</u>	<u>March</u>
All tasks	520	0
Final Report	130	130

E. CONTRACT PERSONNEL

There have been no personnel changes during this period.

F. PROGRAM FOR NEXT INTERVAL

High vacuum discharge tests will be continued and various electrode materials will be tested. Experiments will be performed to evaluate the effect of DC bias on both two surface and single surface

multipactor. As part of the program to predict multipactor, measurements will be made to determine the secondary electron emission threshold voltage for typical materials. Compilation of material for the final report will be started.